Cost Reductions in Offshore Wind through Technology Innovation

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Characteristics of Offshore Wind

- **Opportunities**
  - Better winds
  - Vast resource
  - Proximity to load

- **Challenges**
  - High LCOE
  - High BOS costs
  - Accessibility
  - Inexperience, Immaturity
Offshore Wind @ Sandia

- **Vision**: Promote & accelerate the commercial OW industry and **reduce costs** through **technical innovation**:
  - Siting/Permitting: Sediment Transport & Radar
  - Large offshore HAWT rotors
  - Deepwater VAWT system
  - Structural health and prognostics management
  - Offshore wind farm modeling

- **Sensing, Structural Health, and Prognostics**
- **High-resolution Offshore Wind Farm Modeling**
- **Deepwater Offshore VAWT**
Structural Health and Prognostics Management

**Summary/LCOE Impact**
- Mitigate rising costs for offshore O&M (estimated to be 2-5 times of land-based)
- Maximize energy capture by increasing availability

**Focus Areas**
Simulation of Damage:
1. Identify best operating signatures (sensors) : Damage Detection
2. Analyze effects of damage (state of health and remaining life): Prognostics

**Key Blade Downtime Issues**
- Rotor imbalance
- Trailing edge disbonds
- Leading edge cracks
- Edge-wise vibration
- Erosion
- Lighting
- Icing

Initial Roadmap Report
Damage (Reliability) is a:

- (1) Design issue?
- (2) Monitoring and Inspection issue?
- (3) Combination – tradeoffs in design cost versus operational costs

“Design with Inspection, Monitoring, and Maintenance”
Motivations for a Structural Health and Prognostics Management System

A SHPM system that can be used to:
1. Ensure operations in a desired safe state of health
2. Avoid catastrophic failures through advanced warning
3. Aid in planning of maintenance processes versus more costly unplanned servicing
4. Improve energy capture by avoiding unnecessary shutdown

COE affected in 3 areas

\[
\text{COE} = \text{ICC} \times \text{FCR} + \text{LRC} + \text{O&M} \quad \text{AEP}_{\text{net}}
\]

- COE - Cost of Energy ($/kWh)
- ICC - Initial Capital Cost ($)
- FCR - Fixed Charge Rate (%/yr)
- LRC - Levelized Replacement Cost ($/year)
- O&M - Operations and Maintenance Costs ($/kWh)
- AEP - Annual Energy Production (kWh/yr)

Greater motivation offshore with accessibility issues.
Reduce O&M costs and Maximize Energy Capture
Smart Loads Management

“derating”, “prognostic control”

Increase energy capture and reduce O&M costs with planned maintenance

Secondary, System Level Benefits (e.g. support structure)

Minor Change in Control Strategy

Revenue

Smart Loads Management

Increase energy capture and reduce O&M costs with planned maintenance
**SHPM Economics: Effects of Monthly Wind Resource Variation and level of derating**

The increased energy capture of derating ranges from 1.5% to 10.7% depending on level of derating and monthly variation in the wind resource,

Strong opportunity for return on investment of monitoring system

Table 2: Variations due to monthly wind speed variation in possible revenue increases (using 5 c/kWh), when derating for 1 month instead of shutdown.

<table>
<thead>
<tr>
<th>Derating Level</th>
<th>Low Speed (7 m/s)</th>
<th>High Speed (16.5 m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75% (A)</td>
<td>+$63,800 (+4.9%)</td>
<td>+$140,000 (+10.7%)</td>
</tr>
<tr>
<td>75% (B)</td>
<td>+$53,400 (+4.1%)</td>
<td>+$99,100 (+7.6%)</td>
</tr>
<tr>
<td>50% (A)</td>
<td>+$55,800 (+4.3%)</td>
<td>+$131,000 (+10.0%)</td>
</tr>
<tr>
<td>50% (B)</td>
<td>+$44,500 (+3.4%)</td>
<td>+$73,800 (+5.6%)</td>
</tr>
<tr>
<td>25% (A)</td>
<td>+$35,300 (+2.7%)</td>
<td>+$96,800 (+7.4%)</td>
</tr>
<tr>
<td>25% (B)</td>
<td>+$19,200 (+1.5%)</td>
<td>+$23,900 (+1.8%)</td>
</tr>
</tbody>
</table>

Results for a single 5MW turbine
Is a “Baby Boomer” generation of aging turbines coming?

- 71% of worldwide installations are less than 6 years old
- Varies by region
  - 54% European Market
  - 74% North American Market
  - 87% Asian Market

Current maturity of SHPM technology?
Inflow Variability Study

- Goal: Quantify effect of variable wind inflow on robustness of damage detection with a POD simulations campaign

| Table 3: FAST Simulation Matrix for Each Blade Damage Type. |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Healthy | 1m Dis-bond | 2m Dis-bond | 3m Dis-bond | 4m Dis-bond | 5m Dis-bond | 10m Dis-bond |
| Wind Speed (3 - 25 m/s) | 101     | 101          | 101          | 101          | 101          | 101           | 101           |
| Horizontal Shear (30%, 60%, 90%) | 303     | 303          | 303          | 303          | 303          | 303           | 303           |
| Turbulence (A, B, KHTEST)        | 303     | 303          | 303          | 303          | 303          | 303           | 303           |

- >16,000 simulations with varied extent of damage and varied inflow
- Sensitivities to varying inflow:
  - Wind speed, horizontal shear, and turbulence
- Effect on POD
  - POD improved in certain wind speed ranges (SHM optimization!)

- Waked flow is a subset of the varied inflow conditions: increased turbulence, horizontal shear, and velocity deficit

POD = Probability of Detection
**Large Offshore Rotor Development (100-meter Blade Project)**

- **Summary**
  - Large blade design studies
  - Public domain blade project
  - Reference Models

- **Objectives/Focus Areas**
  - Identify trends and challenges
  - Detailed 100-meter reference designs
  - Targeted follow-on studies: advanced concepts, materials, flutter, manufacturing cost trends, thick airfoils, CFD, optimization

- **Products**
  - Design reports
  - 100-m blade and 13.2 MW turbine reference models

http://largeoffshorerotor.sandia.gov

- **Partners:**
  - None funded, In-kind
  - 70+ users
Sandia Blade Manufacturing Cost Model:

**Approach**

- Components of the Model:
  - Materials, Labor, Capital Equipment

- Input the design characteristics
  - Geometry and BOM from blade design software (NuMAD)
  - Materials cost based on weight or area
  - Labor scaled based on geometry associated with the subtask
  - Capital equipment scaled from typical on-shore blades

*Two principal questions:*

Trends in principal cost components for larger blades?  
Cost trade-offs for SNL100 meter design variants?
Innovative Offshore Vertical-Axis Wind Turbine Rotors Project
A VAWT in deep-water has several inherent advantages. Large reduction in offshore costs requires non-incremental solutions.
## Rotor Structural Design Configurations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Darrieus, V</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>2, 3</td>
</tr>
<tr>
<td>Tip Chord Length</td>
<td>2m, 3m</td>
</tr>
<tr>
<td>Composite Material:</td>
<td>Glass/Epoxy, Carbon/Epoxy</td>
</tr>
<tr>
<td>Tapering Scheme (Darrieus only, V-VAWTS used Single Taper)</td>
<td>No Taper, Single Taper, Double Taper</td>
</tr>
<tr>
<td>Curvature or Power Law Exponent (V-VAWT)</td>
<td>n=1, n=3, n=5</td>
</tr>
</tbody>
</table>

![Graph of D and V VAWT Shapes](image)

![ANSYS Beam Models of D and V VAWTS](image)
Rotor Aero Design Population

- **24 Candidate Rotor Design External Shapes**
  - **12 Darrieus:**
    - large/small chord
    - single/double/no blade taper
    - two/three blades
  - **12 “V”-Rotors:**
    - large/small chord
    - power law shape exponent = 1/3/5
    - two/three blades

- **Constraints**
  - Max radius = 54 m
  - Same capture area
  - NACA 0021 airfoil section
Platform Options

- Evaluate two main platform designs:
  - WindFloat Semi-Submersible
  - Hywind Spar

- Alter size as a function of the VAWT topside input.
Cost Analysis Components

- Offshore Wind Farm Cost
  - Balance of System Costs
    - Transportation
    - Installation
    - Electrical Interconnection
    - Other
  - Operations & Maintenance Costs
  - Turbine Capital Costs
    - Rotor
    - Drivetrain
    - Platform/Support Structure
    - Control & Monitoring System
    - Marinization
- Total of 31 offshore VAWT rotors analyzed

- A number of turbine, platform, drive-train configurations were considered (5 MW rotors)
  - Rotor mass a critical parameter for rotor and platform costs
  - Rotor RPM another key parameter
System Trade-offs:

AEP, RPM, Drivetrain

Rotor vs Platform

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DC_3B_LCDT</th>
<th>DC_2B_LCDT</th>
<th>DG_3B_SCDT</th>
<th>DG_2B_SCDT</th>
<th>VC_2B_LCN5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>Carbon</td>
<td>Glass</td>
<td>Glass</td>
<td>Carbon</td>
<td></td>
</tr>
<tr>
<td>3 blades Large chord</td>
<td>2 blades</td>
<td>3 blades</td>
<td>2 blades</td>
<td>2 blades</td>
<td></td>
</tr>
<tr>
<td>Turbine AEP (MW-hr)</td>
<td>20069</td>
<td>18443</td>
<td>18880</td>
<td>17004</td>
<td>18992</td>
</tr>
<tr>
<td>Rotor Speed (RPM)</td>
<td>6.30</td>
<td>7.20</td>
<td>7.20</td>
<td>8.25</td>
<td>7.40</td>
</tr>
<tr>
<td>Drive-train Cost (M USD)</td>
<td>3.7</td>
<td>3.2</td>
<td>3.2</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Rotor Cost (M USD)</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Spar Platform Cost (M USD)</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>
Concluding Remarks

- Cost reductions are needed to unlock vast potential for offshore wind.

- Sandia performing R&D in targeted technology areas.

- A systems approach to integrating technology solutions would be beneficial to explore the lowest cost area of the (offshore) wind design space.

- “System” not only the capital equipment but also include the important decisions and costs of the operating system during their lifetime.